

Realizing the Long Range Plan at RHIC

Opportunities in Spin and Cold QCD Physics

SPIN + Cold QCD Recommendations

*The upgraded RHIC facility provides unique capabilities that must be utilized to explore the properties and phases of quark and gluon matter in the high temperatures of the early universe and to explore the **spin structure of the proton.***

- LRP recommendation I

*We recommend a high-energy high-luminosity polarized **EIC** as the highest priority for new facility construction following the completion of FRIB.*

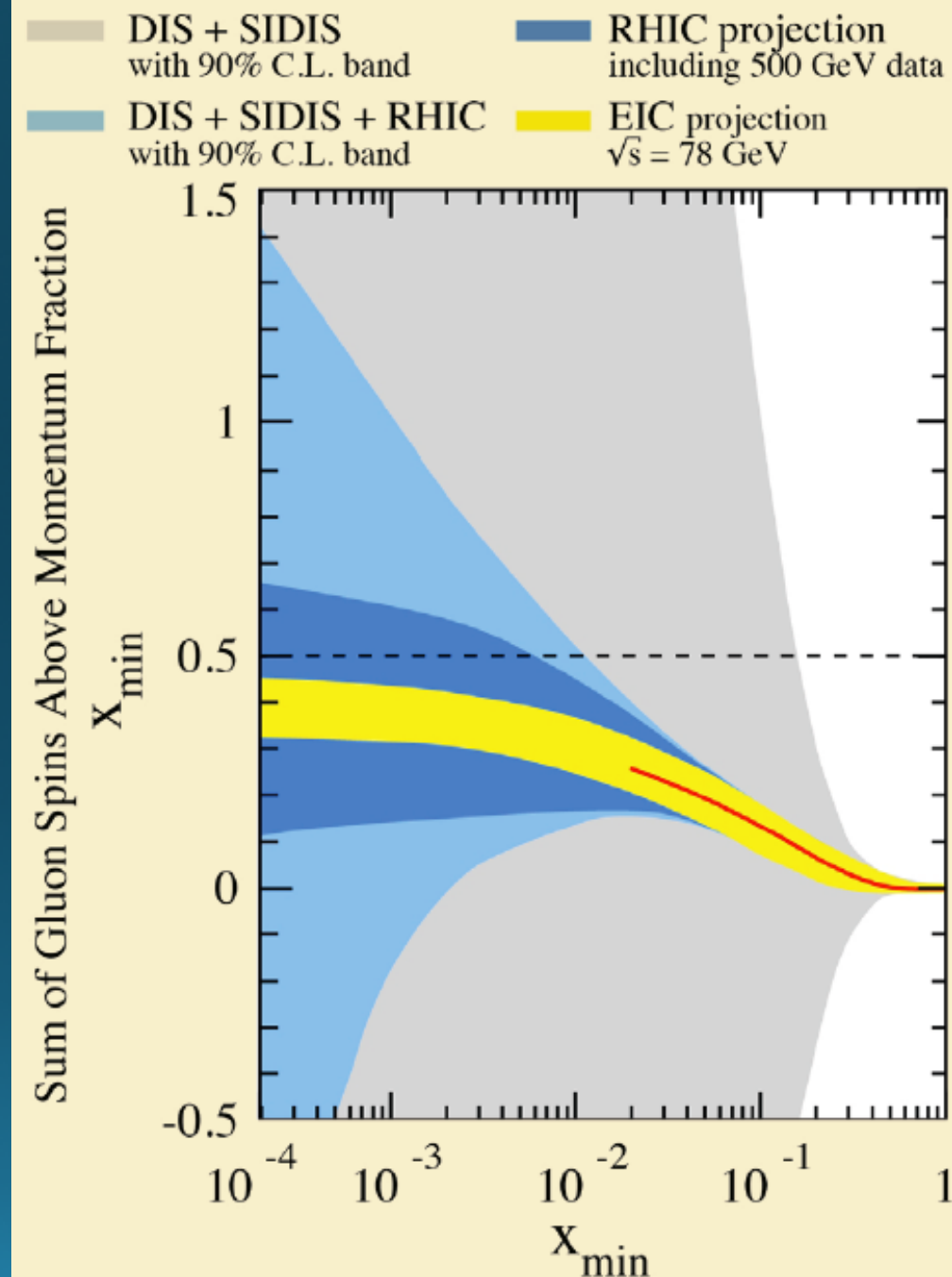
- LRP recommendation III

Gluon Spin [page 36]

- RHIC inclusive jet and pion asymmetries provided the first evidence of significant gluon polarization inside the proton.
- This contribution was highlighted as a significant achievement since the last LRP.

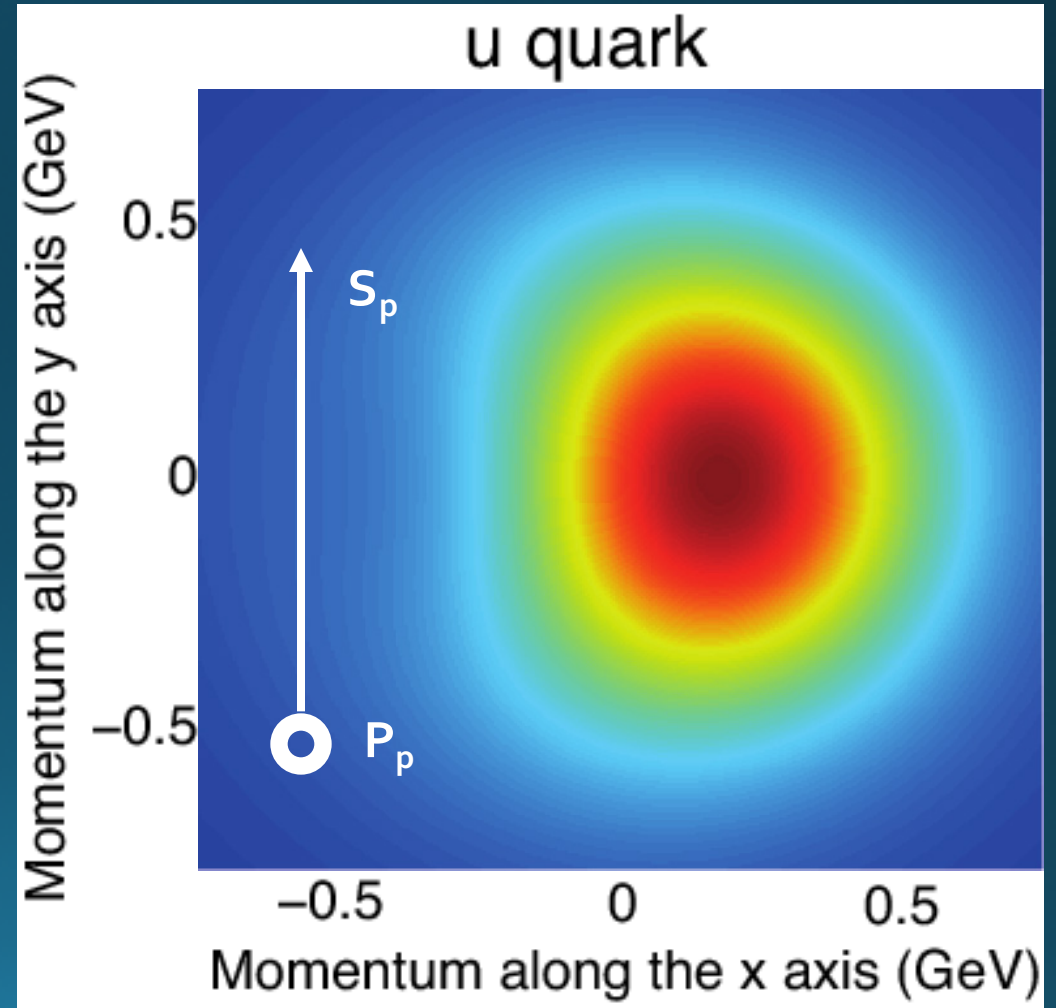
- RHIC could push sensitivity to lower x gluons ($\sim 10^{-3}$) by reconstructing dijets in the forward region

- DATA : $p+p \sqrt{s} = 500 \text{ GeV } 1.1 \text{ fb}^{-1}$
- DETECTOR: forward charged and neutral particle detection for jet reconstruction plus tracker for vertexing.



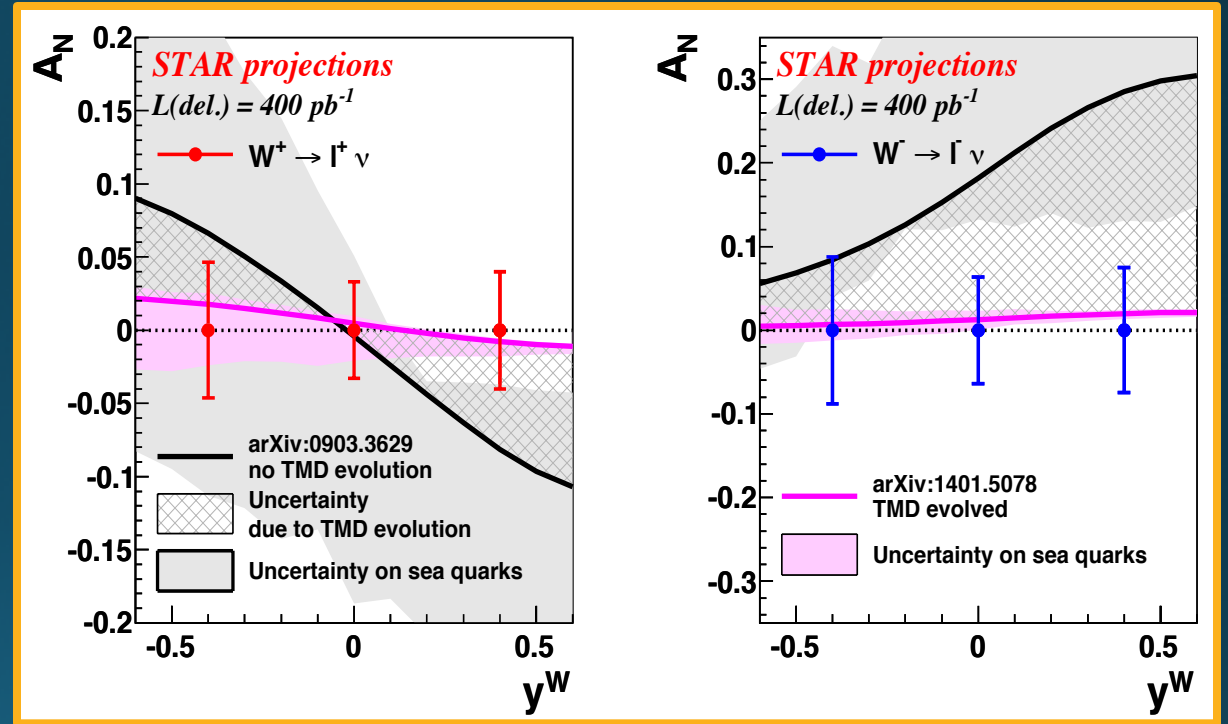
Transverse Momentum Distributions [page 16]

- Expand traditional 1D momentum PDF's \Rightarrow 3D !
- Correlations between proton spin and parton transverse momentum are sensitive to orbital angular momentum. Effects are encapsulated in a PDF called the **Sivers** function.
- Theoretical efforts initially driven by QCD spin community but are essential in particle physics as well, for example in describing Higgs production.
- As in collinear case, interpretation of data rests on robustness of the theoretical framework and experimental tests of **factorization** and **evolution**.



Transverse Momentum Distributions [page 18]

- RHIC will test TMD factorization and evolution via measurements of the single spin asymmetry A_{UT} of reconstructed W^+ , W^- and Z^0 bosons and forward Drell-Yan e^+e^- pairs.
- Asymmetries also provide new constraints on sea-quark Sivers functions.



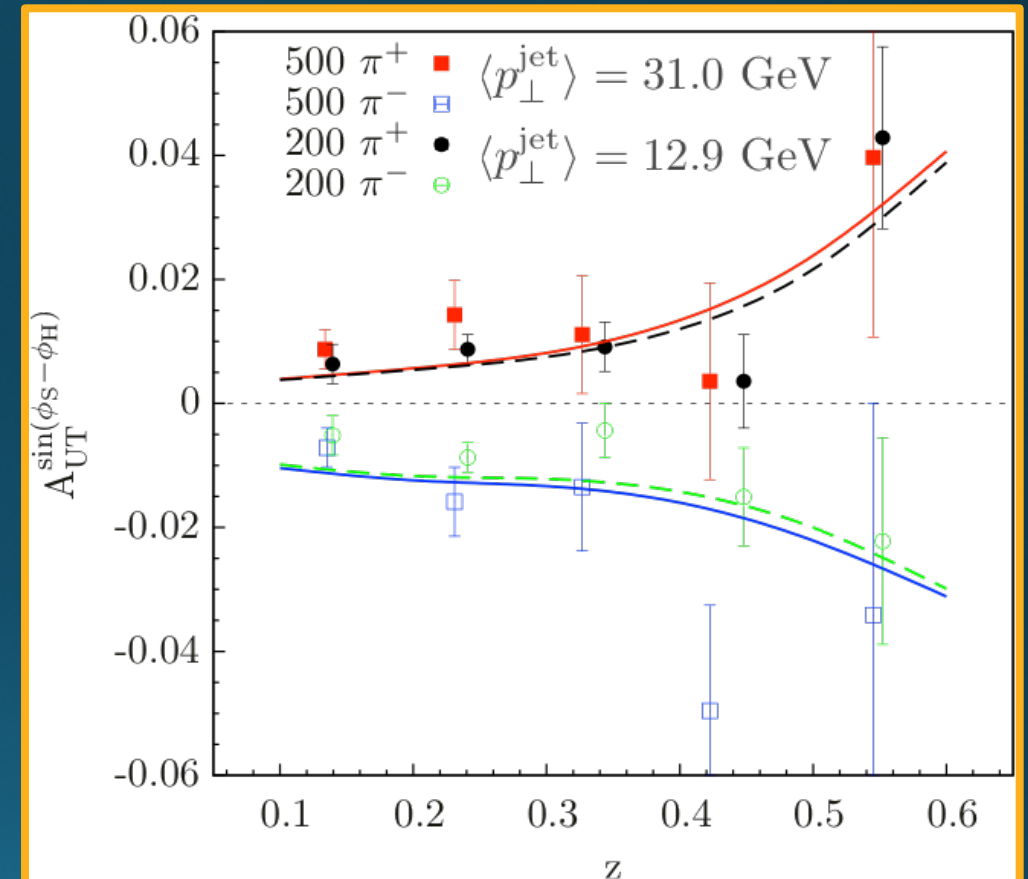
DATA : $p+p \sqrt{s} = 500 \text{ GeV } 400 \text{ pb}^{-1}$

DETECTOR: W/Z needs EMCal and charge sign discrimination at mid-rapidity.
DY needs forward EMCal + pre/post shower for QCD background suppression.

Transverse Momentum Distributions [page 18]

- TMD's may also be studied in fragmentation. The **Collins FF** encapsulates the correlation between the transverse spin of the quark and the transverse momentum of the fragmentation hadrons.

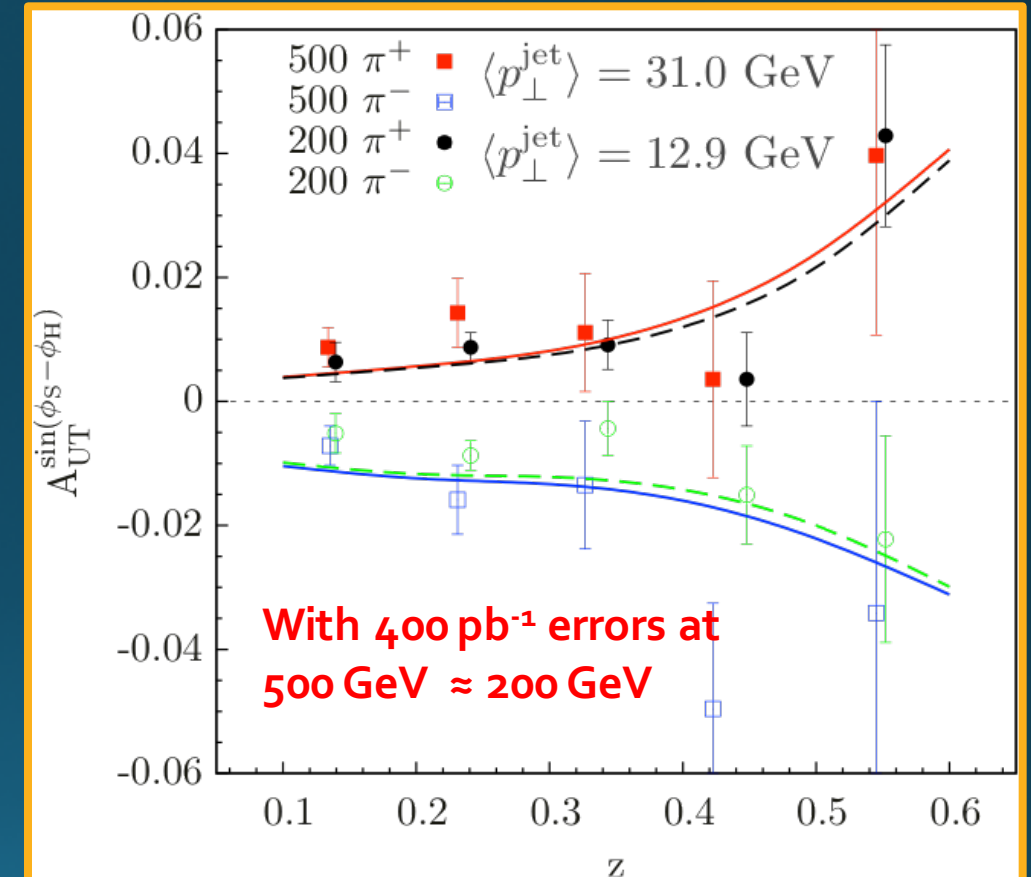
- The Collins function is accessible the single spin asymmetry A_{UT} of the azimuthal distribution of charged pions, kaons and protons inside of a jet.
- Measurements of A_{UT} will test the universality and evolution of the Collins FF.



Transverse Momentum Distributions [page 18]

- TMD's may also be studied in fragmentation. The **Collins FF** encapsulates the correlation between the transverse spin of the quark and the transverse momentum of the fragmentation hadrons.

- The Collins function is accessible the single spin asymmetry A_{UT} of the azimuthal distribution of charged pions, kaons and protons inside of a jet.
- Measurements of A_{UT} will test the universality and evolution of the Collins FF.

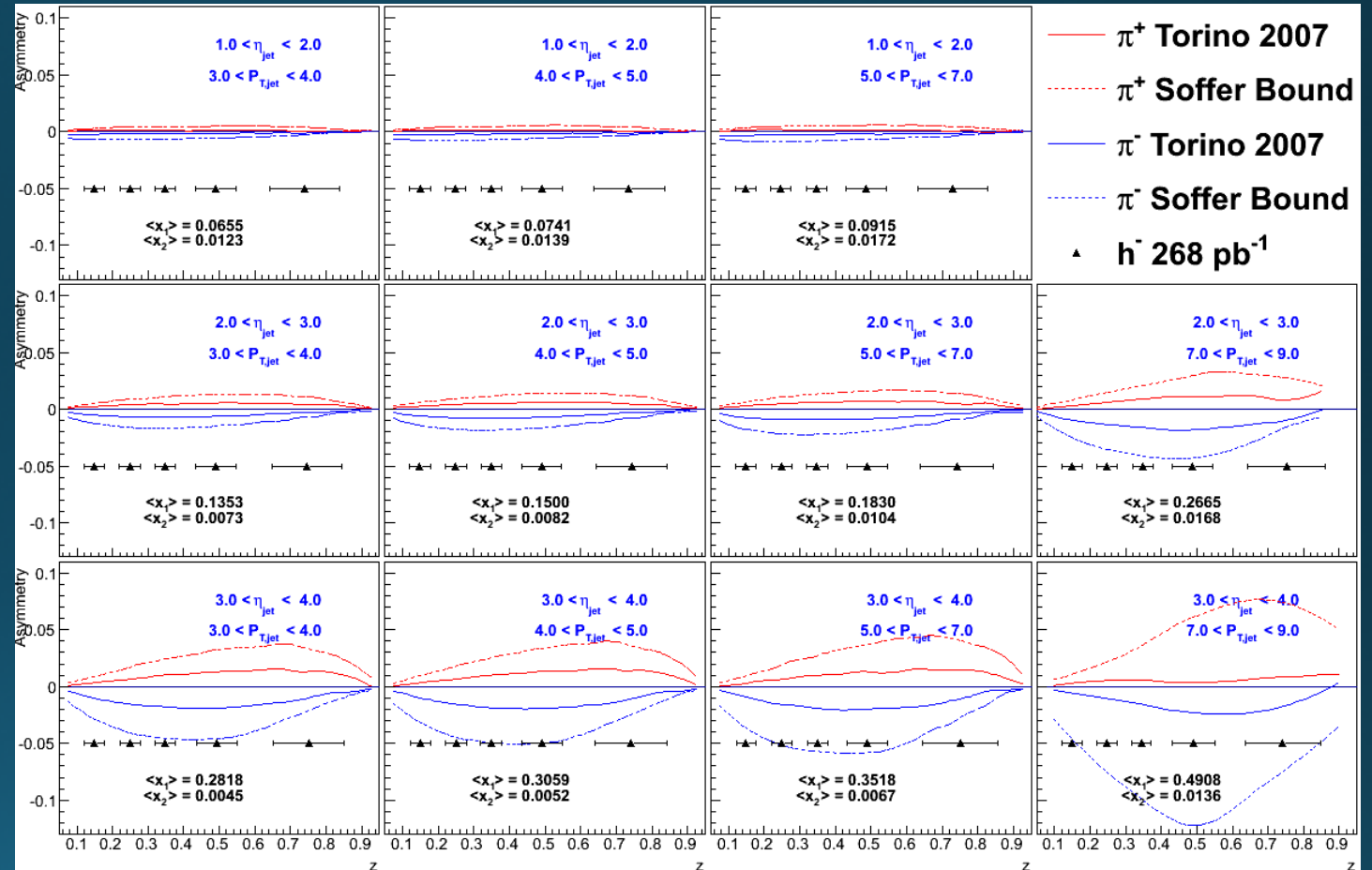


DATA : p+p $\sqrt{s} = 500$ GeV 400 pb⁻¹

DETECTOR: mid-rapidity pion, kaon and proton PID, charged and neutral particle detection for jet reconstruction and tracker for vertexing.

Transverse Momentum Distributions [page 18]

- Mid-rapidity A_{UT} samples an x range of 0.02-0.2.
- RHIC could push sensitivity to high x (> 0.3) as well as lower x ($\sim 10^{-3}$) by reconstructing jets and charged hadrons (h^+/h^-) in the forward direction.
- Measurements of A_{UT} will test the universality and evolution of the Collins FF.



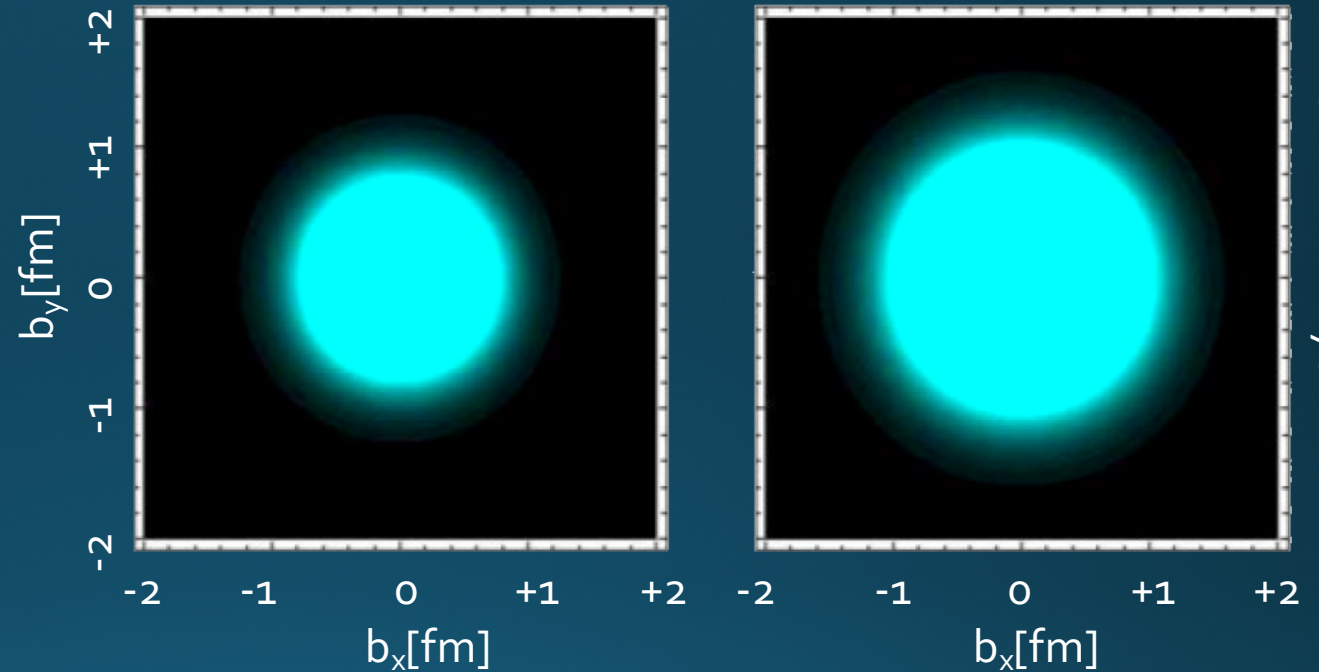
DATA : $p+p$ $\sqrt{s} = 500 \text{ GeV}$ 1.1 fb^{-1}

DETECTOR: Charged sign separation for h^+/h^- (no PID), charged and neutral particle detection for jet reconstruction and tracking for vertexing.

Generalized Parton Distributions [page 16]

- GPD's provide a snapshot of the spatial distributions, as a function of momentum fraction, of the quarks and gluons inside the proton.

- RHIC can access the GPD E function for gluons via measurements of A_{UT} of J/ψ in ultra-peripheral collisions.
- A significant asymmetry would be the **FIRST** sign of a non-zero GPD E_g .
- GPD E_g is sensitive to spin-orbit correlations and provides input on **angular momentum** component of the spin puzzle.



arXiv:1212.1701

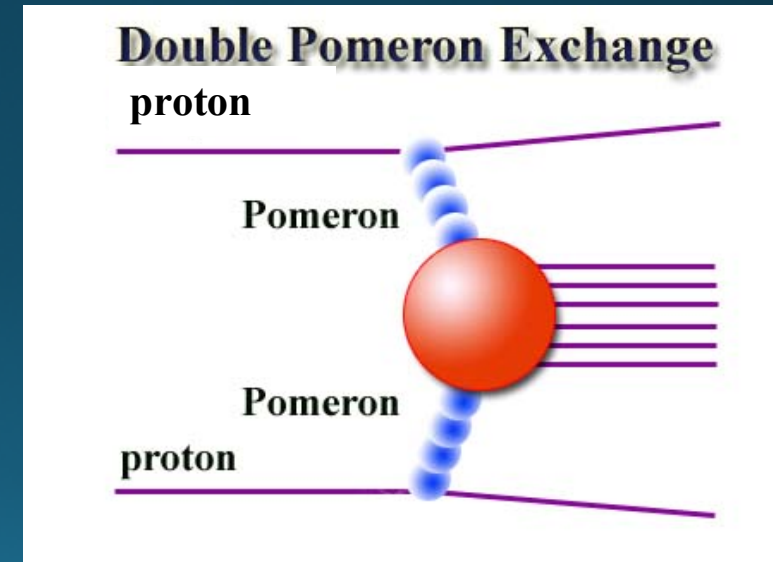
DATA : $p+p \sqrt{s} = 500 \text{ GeV } 400 \text{ pb}^{-1}$, $p+A \sqrt{s} = 200 \text{ GeV } 1.75 \text{ pb}^{-1}$

DETECTOR: EMCals to reconstruct mid-rapidity J/ψ and Roman pots to reconstruct elastically scattered proton

Gluon Spectroscopy [page 19]

- The nature of the strong force allows gluons to interact with each other, suggesting that gluons could bind together and form new states of gluonic matter called glueballs.
- Search for exotic states ongoing at Hall D at JLAB, LHCb and soon at Belle-II.

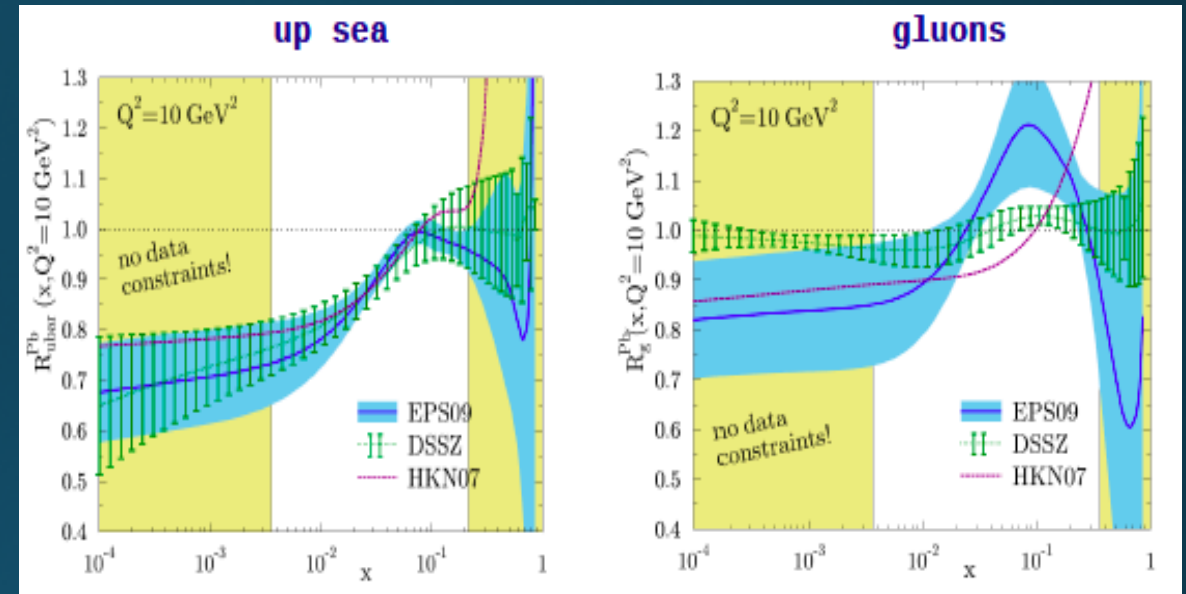
- **Double Pomeron Exchange** in central diffractive events is a potential channel for glueball production.
- DPE events are characterized by two elastically scattered protons at beamline rapidity and one or more pairs of mesons at mid-rapidity.
- RHIC can tag central production events using the upgraded Roman Pot System that was installed and operated in run 15.



DATA : $p+p$ $\sqrt{s} = 500$ and 200 GeV DETECTOR: charge separated π , K PID at mid-rapidity and Roman Pots

Quark and Gluon Properties in Nuclei [page 20]

- Decades of DIS data serve as input to the quark and gluon momentum distributions in proton. Limited data indicates that these PDFs change when the proton resides inside nuclear matter.
- DGLAP predicts Q^2 , but not A or x dependence. Saturation models predict A and x , but only a limited range of Q^2 .



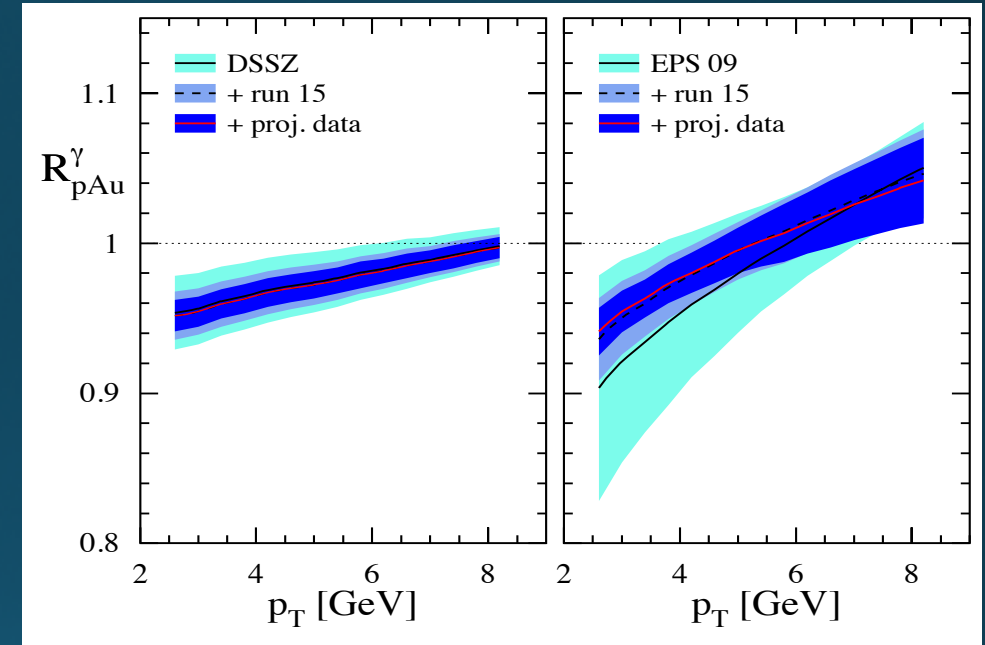
- Need an **A-Scan** and large **Q^2 lever arm** for fixed x in order to reduce existing errors on nPDFs and test saturation models. **RHIC** plays pivotal role in both of these areas!

DATA : $p+p \sqrt{s} = 200 \text{ GeV } 300 \text{ pb}^{-1}$
 $p+Au \sqrt{s} = 200 \text{ GeV } 1.8 \text{ pb}^{-1}$
 $p+Al \sqrt{s} = 200 \text{ GeV } 12.6 \text{ pb}^{-1}$

Quark and Gluon Properties in Nuclei [page 20]

- Decades of DIS data serve as input to the quark and gluon momentum distributions in proton. Limited data indicates that these PDFs change when the proton resides inside nuclear matter.
- DGLAP predicts Q^2 , but not A or x dependence. Saturation models predict A and x , but only a limited range of Q^2 .

- Need an **A-Scan** and large **Q^2 lever arm** for fixed x in order to reduce existing errors on nPDFs and test saturation models. **RHIC plays pivotal role in both of these areas!**
- Channels include **direct photon** for gluon



DATA : $p+p \sqrt{s} = 200 \text{ GeV } 300 \text{ pb}^{-1}$
 $p+Au \sqrt{s} = 200 \text{ GeV } 1.8 \text{ pb}^{-1}$
 $p+Al \sqrt{s} = 200 \text{ GeV } 12.6 \text{ pb}^{-1}$

DETECTOR:

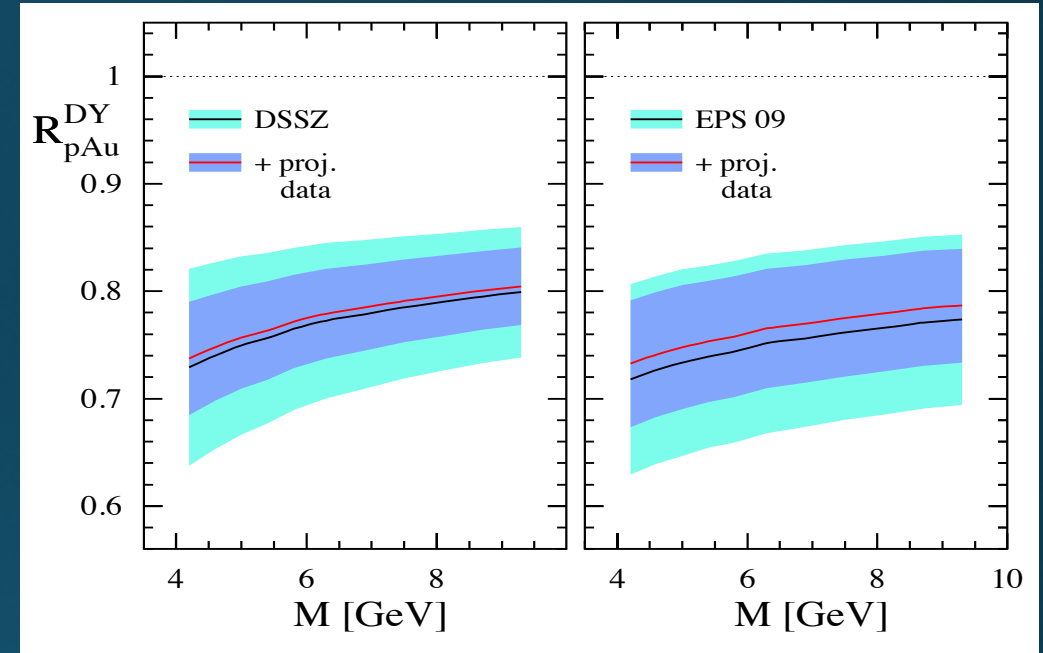
Direct - γ needs forward EMCal+preshower.

Quark and Gluon Properties in Nuclei [page 20]

- Decades of DIS data serve as input to the quark and gluon momentum distributions in proton. Limited data indicates that these PDFs change when the proton resides inside nuclear matter.
- DGLAP predicts Q^2 , but not A or x dependence. Saturation models predict A and x , but only a limited range of Q^2 .

- Need an **A-Scan** and large **Q^2 lever arm** for fixed x in order to reduce existing errors on nPDFs and test saturation models. **RHIC plays pivotal role in both of these areas!**

- Channels include **direct photon** for gluon and **Drell-Yan R_{pA}** for sea quarks nPDFs.



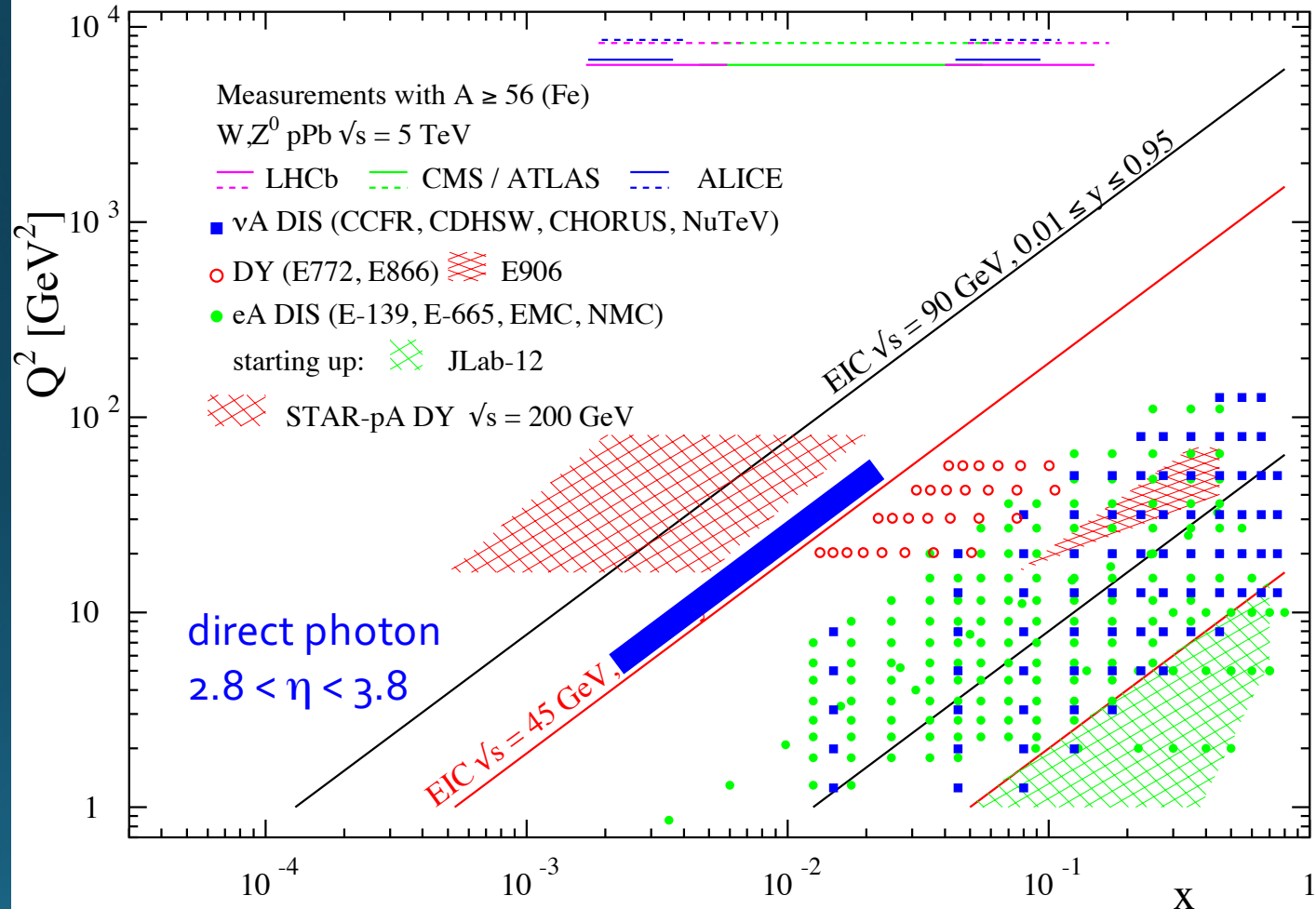
DATA : $p+p \sqrt{s} = 200 \text{ GeV } 300 \text{ pb}^{-1}$
 $p+Au \sqrt{s} = 200 \text{ GeV } 1.8 \text{ pb}^{-1}$
 $p+Al \sqrt{s} = 200 \text{ GeV } 12.6 \text{ pb}^{-1}$

DETECTOR:

Direct - γ needs forward EMCal+preshower.
DY needs forward EMCal+HCAL+tracker package.

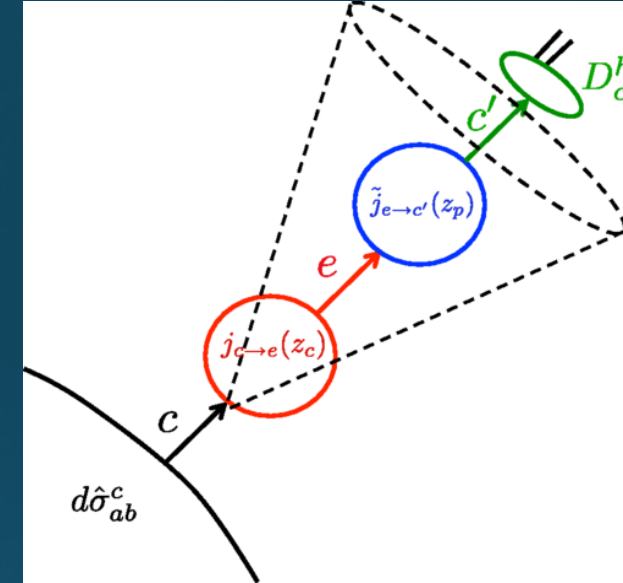
Quark Properties in Nuclei [page 20]

- LHC constraints are minimal due to high Q^2 .
- Kinematic space of RHIC measurements is different but complementary to that proposed by the EIC.



Quark Properties in Nuclei [page 20]

- Recent work by Kaufmann, Mukherjee and Vogelsang proposes to access fragmentation functions by taking the ratio of jets yields with identified hadrons to inclusive jet yields.
- These techniques can be exploited to study how these FF change with inside nuclear matter.

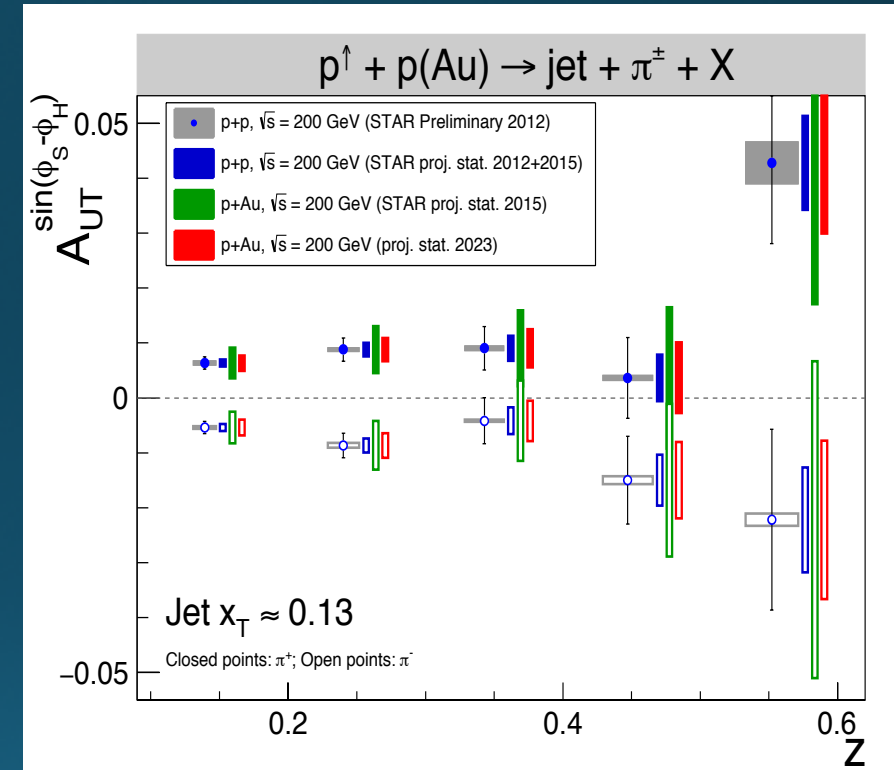
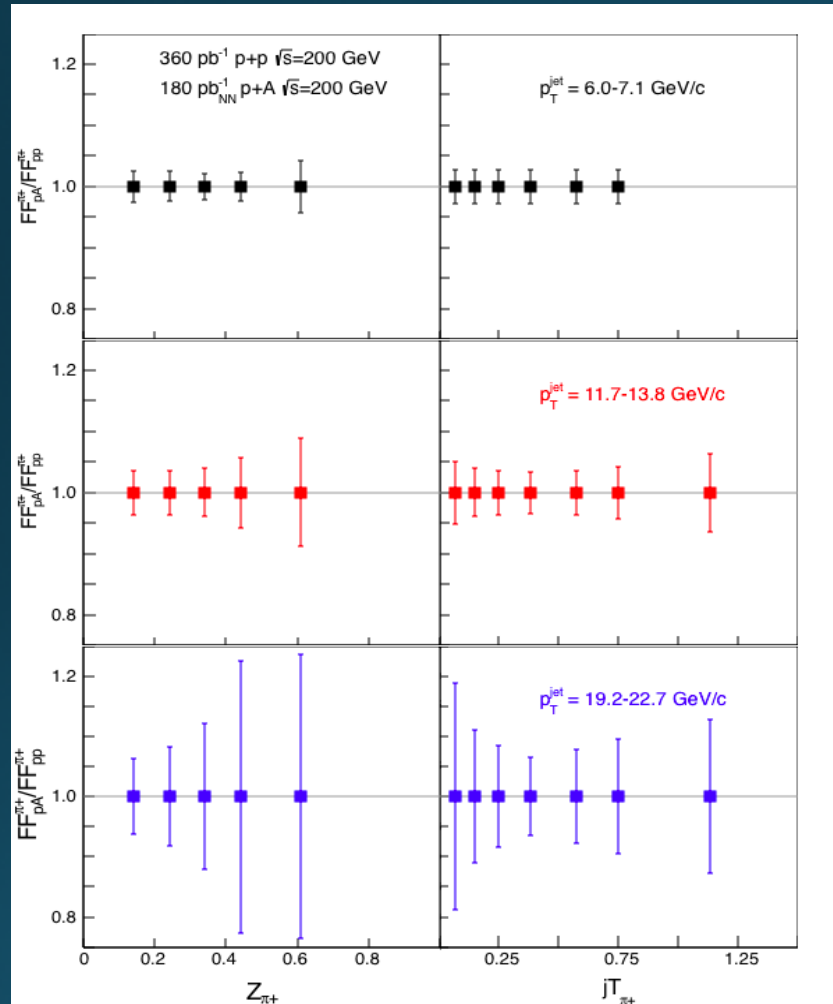


- The p+p collisions at RHIC provide access to the gluon FF.
- RHIC's ability to perform an A scan provides unique insights into nuclear effects during fragmentation.

DATA : p+p $\sqrt{s} = 200$ GeV 300 pb⁻¹
p+Au $\sqrt{s} = 200$ GeV 1.8 pb⁻¹
p+Al $\sqrt{s} = 200$ GeV 12.6 pb⁻¹

DETECTOR: Pion, Kaon and Proton PID and charged + neutral particle detection for jet reconstruction.

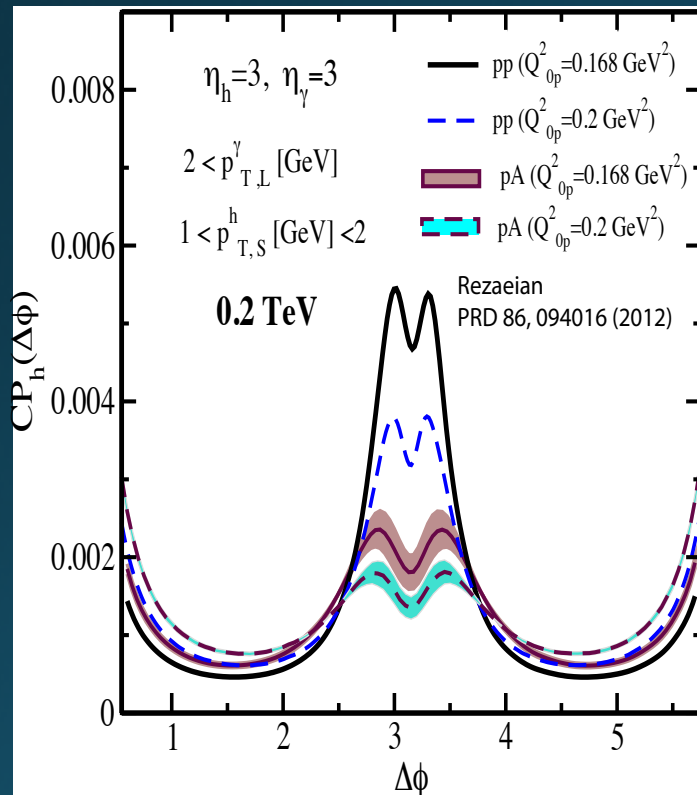
Quark Properties in Nuclei [page 20]



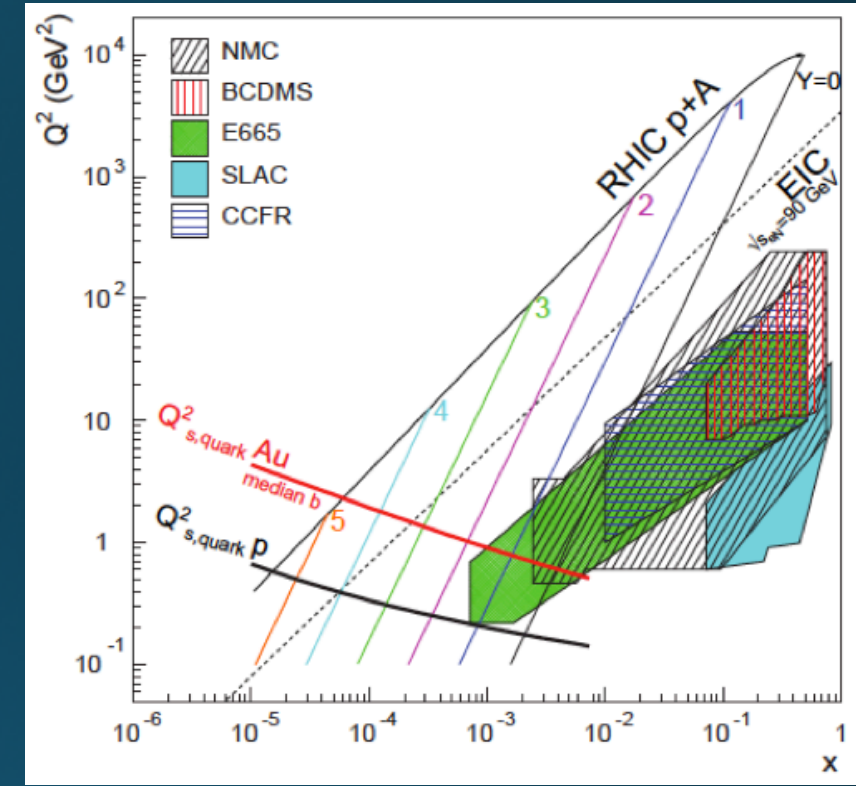
We can also study spin dependent fragmentation effects – completely new and unique to RHIC!

Gluon Saturation [page 37]

Rapid rise of gluon distribution at low x is due to gluon splitting. Eventually gluon recombination dominates and distribution must turn over. This point is called the saturation scale Q_s .



- The clearest signals to detect the onset of saturation at RHIC are correlation observables such as γ +jet and di-jets in the forward direction.
- Aids in theoretical development and design for EIC.



DATA : p+p $\sqrt{s} = 200 \text{ GeV}$ 300 pb^{-1}
 p+Au $\sqrt{s} = 200 \text{ GeV}$ 1.8 pb^{-1}
 p+Al $\sqrt{s} = 200 \text{ GeV}$ 12.6 pb^{-1}

DETECTOR: Direct γ PID and charged + neutral particle detection for jet reconstruction.

Run Summary

RHIC's ability to collide polarized protons and a variety of ion species allows it to make very **unique** contributions to the goals outlined by the cold QCD and Spin community in the 2015 Long Range Plan.

***Requires Forward Upgrades**

BEAMS	\sqrt{s} (GeV)	\mathcal{L} (pb ⁻¹)	PHYSICS MOTIVATION
p [↑] +p	500	400 12 wks	<ol style="list-style-type: none"> 1. TMD factorization and Evolution 2. Sea-Quark Sivers Function 3. Universality and Evolution of Collins FF 4. Constraints on \bar{d}/\bar{u} PDFs 5. Gluon GPD E 6. Glueball Search 7. Low/High x TMDs * 8. Low x ΔG *
p [↑] +p p→ + p→		1100 10 wks	
p [↑] +p	200	300 8 wks	<ol style="list-style-type: none"> 1. Nuclear PDFs (DY*) 2. Proton FFs in nuclear matter 3. Spin dependent FF in nuclear matter
p [↑] +Au	200	1.8 8 wks	A dependence of <ol style="list-style-type: none"> 1. Nuclear PDFs (DY*) 2. Proton FF in nuclear matter 3. Spin dependent FF in nuclear matter 4. Gluon saturation signals *
p [↑] +Al	200	12.6 8 wks	SAME as p [↑] +Au

This talk was a birds-eye view of some compelling cold QCD physics. For more details please see:

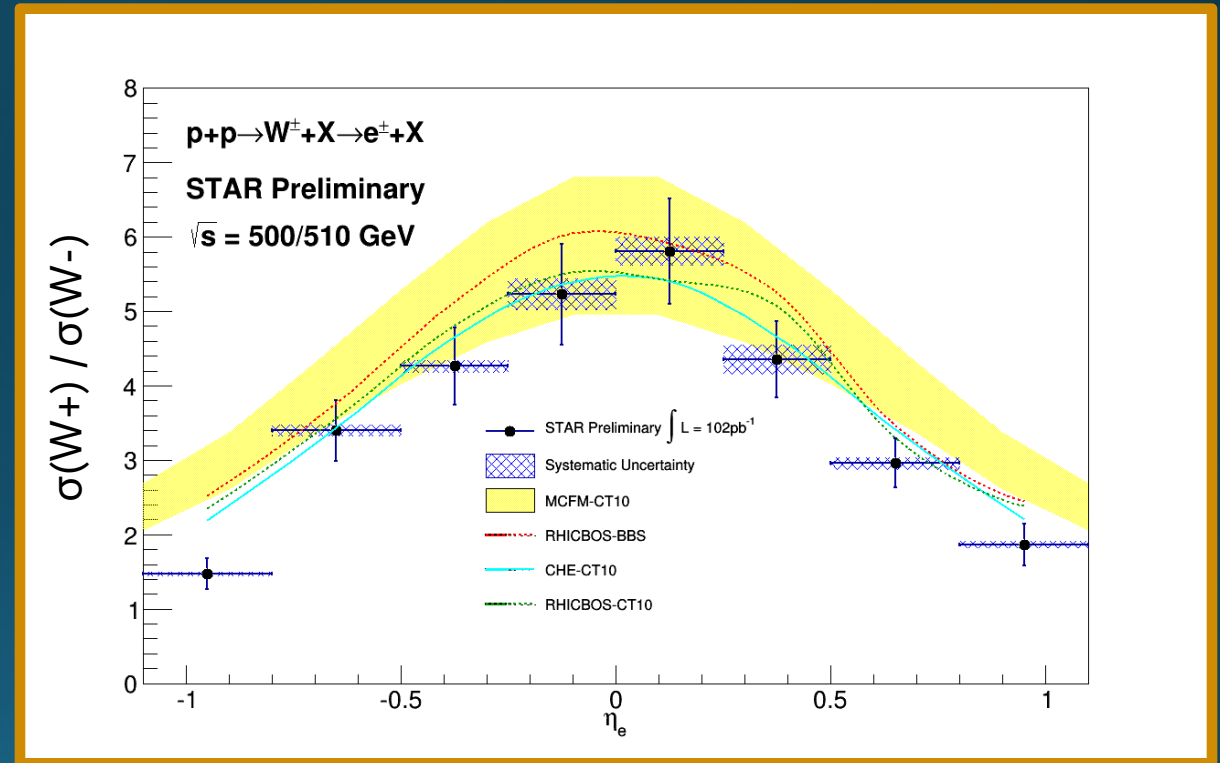
- Cold QCD + Spin plenary talk by Elke Aschenauer
 - <https://www.bnl.gov/aum2016/content/plenary/ps1.php>
- RHIC Cold QCD and Spin White paper
 - [arXiv:1602.03922](https://arxiv.org/abs/1602.03922)
- NSAC Long Range Plan Document
 - <http://science.energy.gov/np/nsac/>

More still?

Anti-Quark Momentum Distributions [page 15]

- Sea anti-quark momentum distributions are not highly constrained by SIDIS data
- Ratio of \bar{d}/\bar{u} is sensitive to the flavor asymmetry of the sea first seen by NMC and NA51 and mapped out by FNAL 866.

- RHIC constrains \bar{d}/\bar{u} via measurements of the W^+/W^- cross-section ratio.
- Including Run 13 + 17 data will reduce statistical error by a factor of 3.



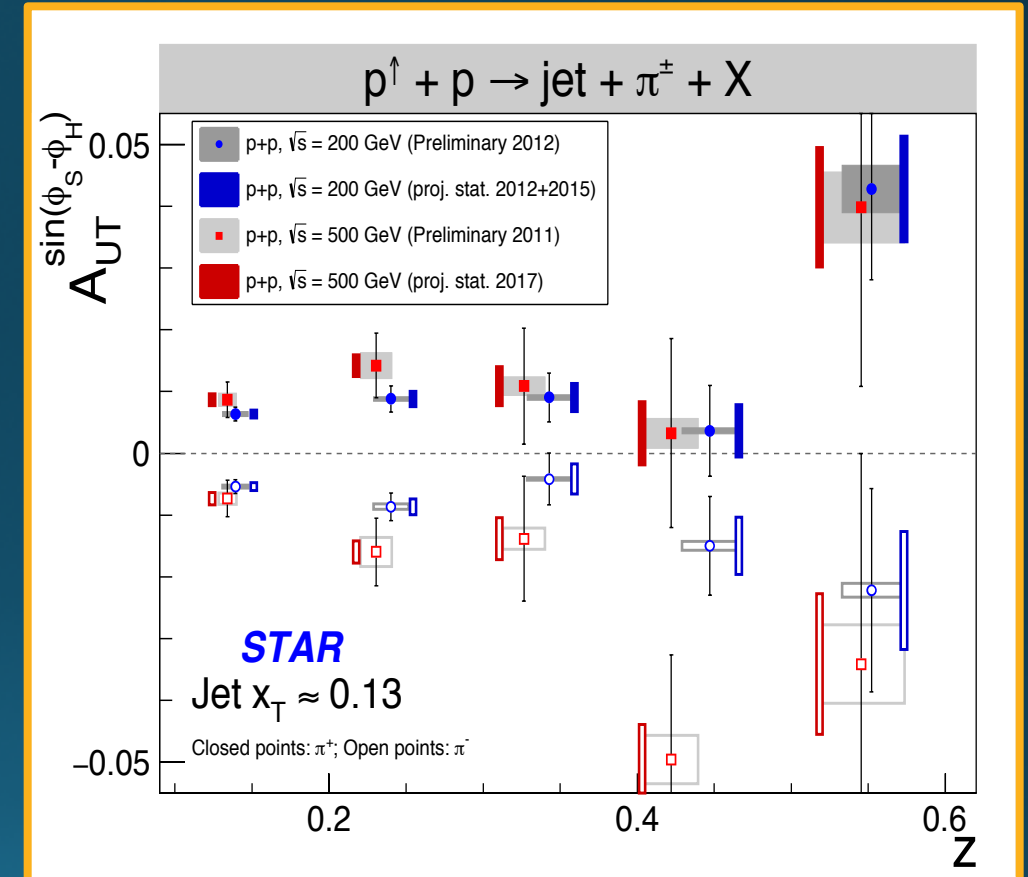
DATA : $p+p \sqrt{s} = 500 \text{ GeV } 400 \text{ pb}^{-1}$

DETECTOR: EMCal and charge sign discrimination for midrapidity tracks.

Transverse Momentum Distributions [page 18]

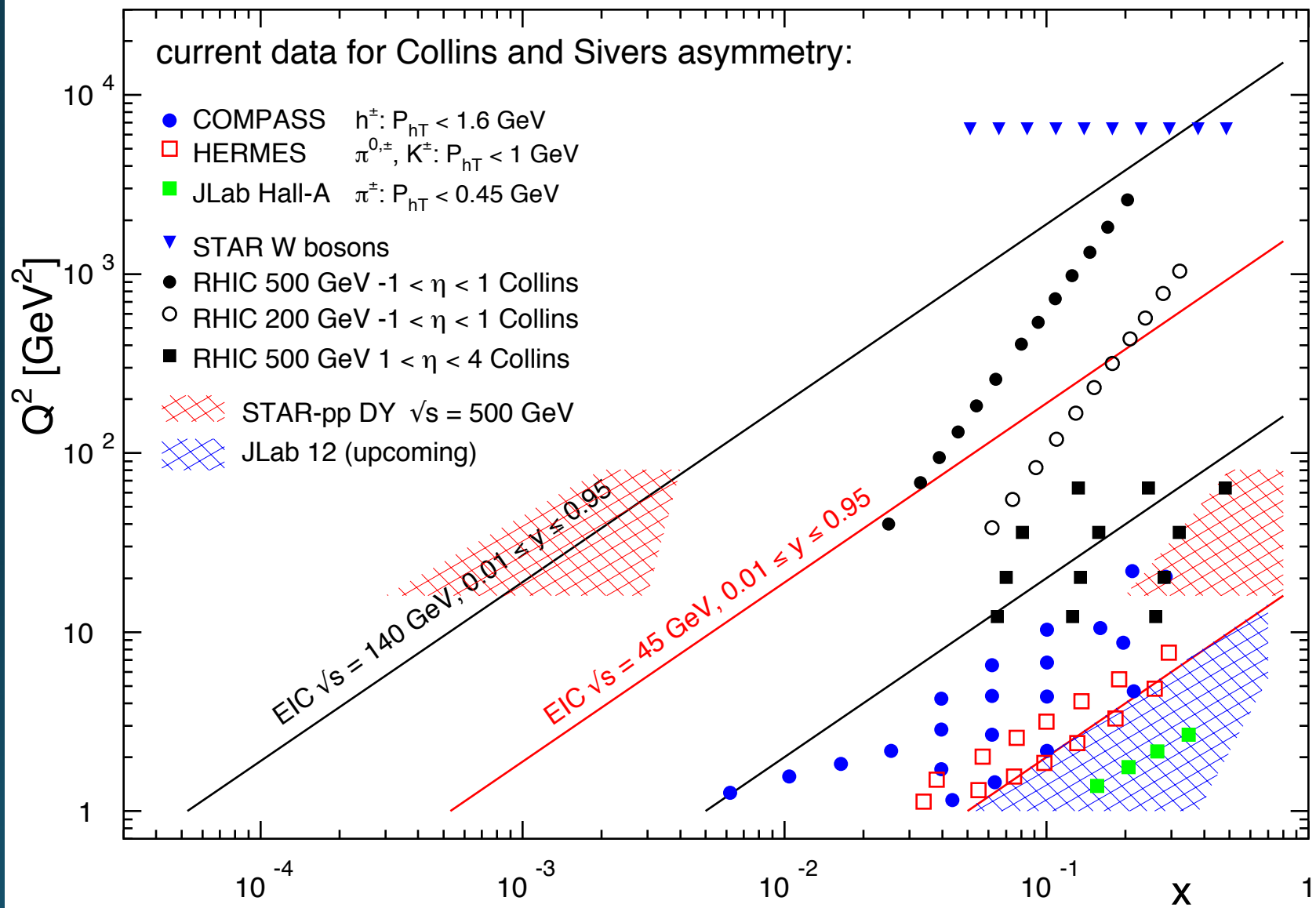
- TMD's may also be studied in fragmentation. The **Collins FF** encapsulates the correlation between the transverse spin of the quark and the transverse momentum of the fragmentation hadrons.

- The Collins function is accessible via measurements of the single spin asymmetry A_{UT} of the azimuthal distribution of charged pions, kaons and protons inside of a jet.
- Measurements of A_{UT} will test the universality and evolution of the Collins FF.



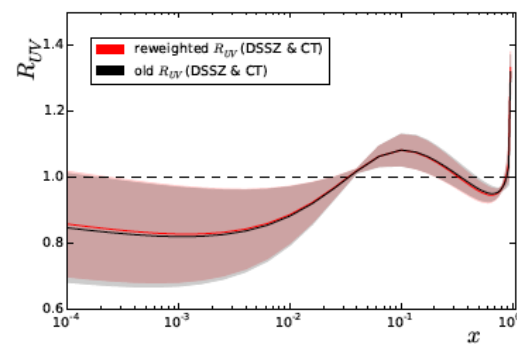
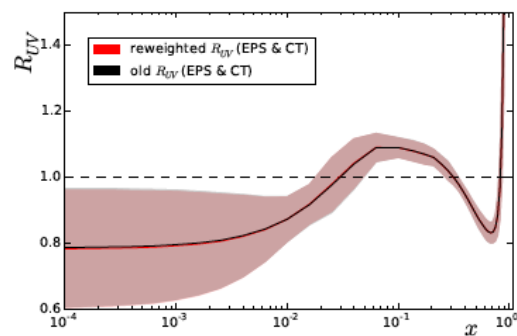
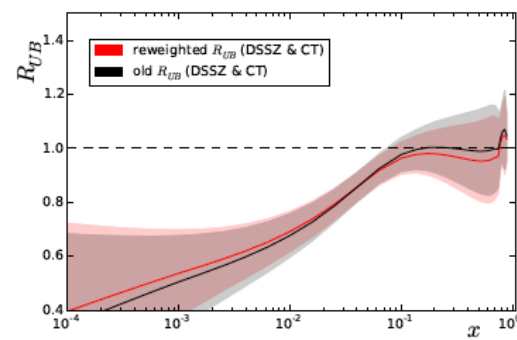
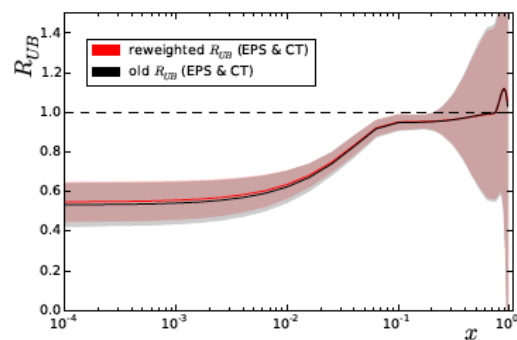
DATA : $p+p \sqrt{s} = 500 \text{ GeV } 400 \text{ pb}^{-1}$

DETECTOR: Pion, Kaon and Proton PID and charged + neutral particle detection for jet reconstruction.

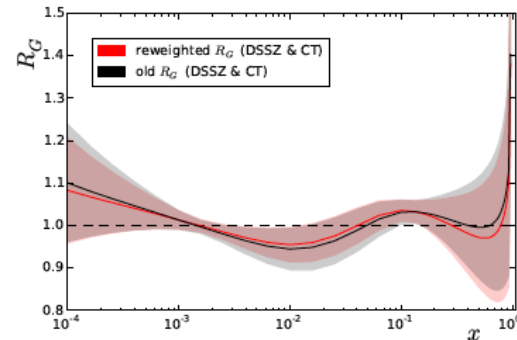
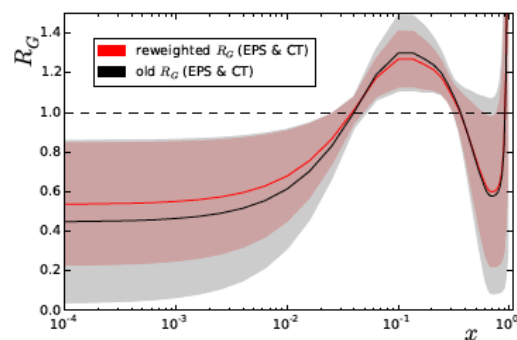


EPS-09

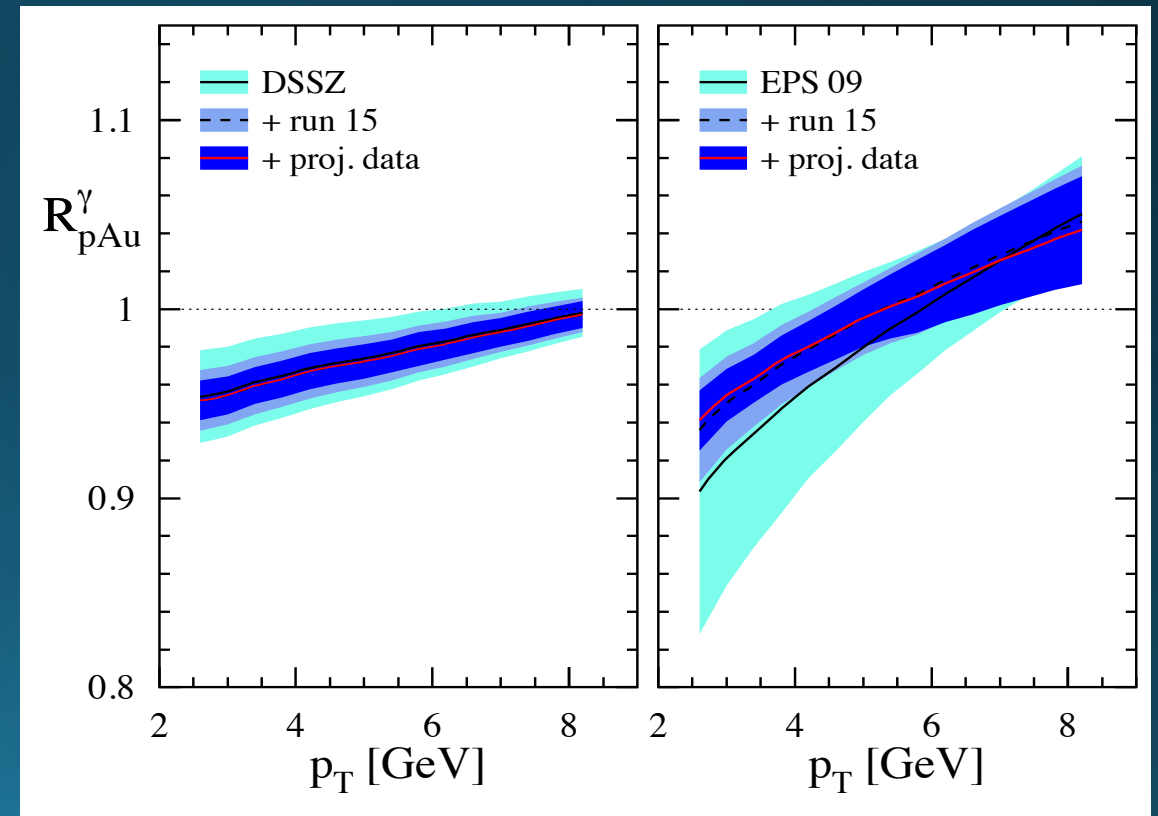
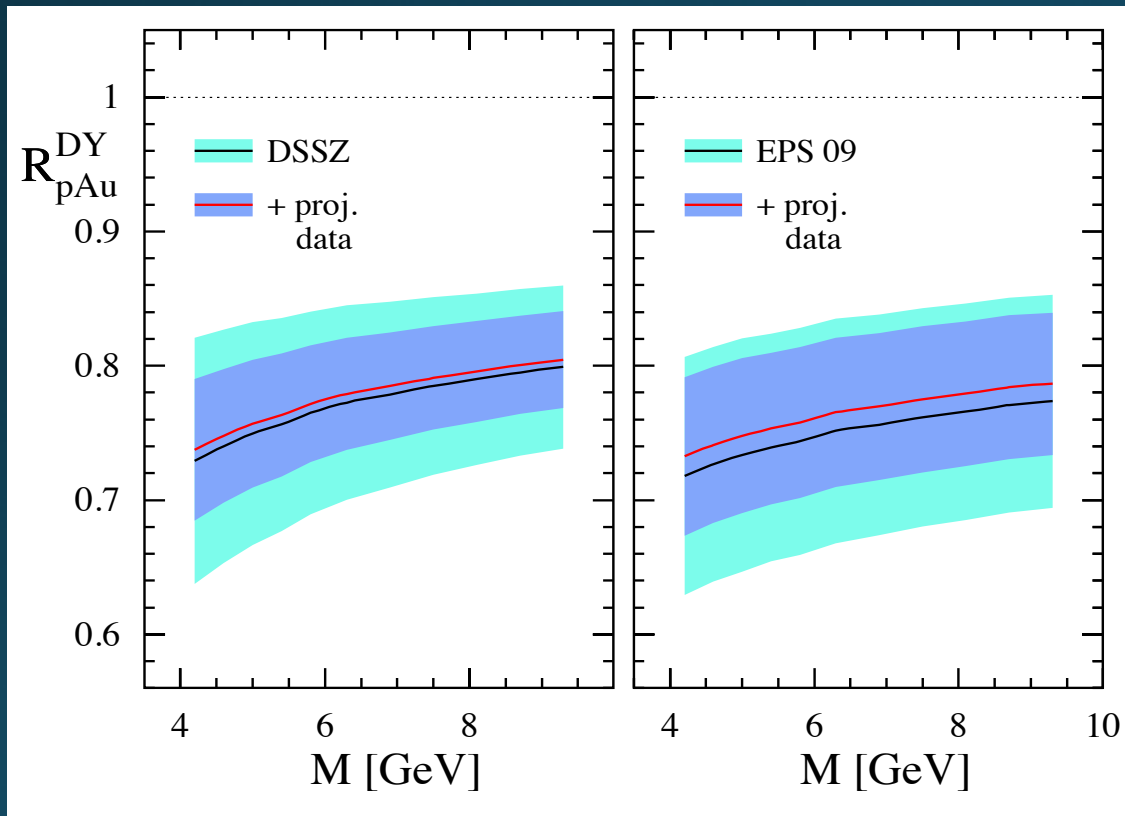
DSSZ

Valence
QuarkSea
Quark

gluons

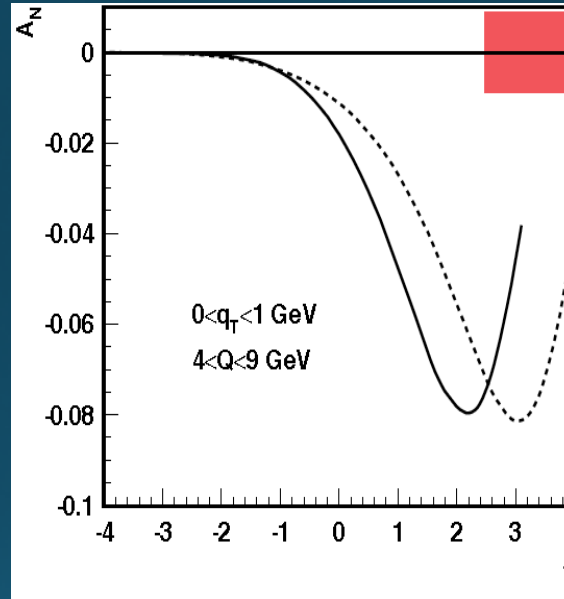
N. Armesto, *et al.*, arXiv:1512.01528

Projected constraints from Direct γ and DY R_{pA}

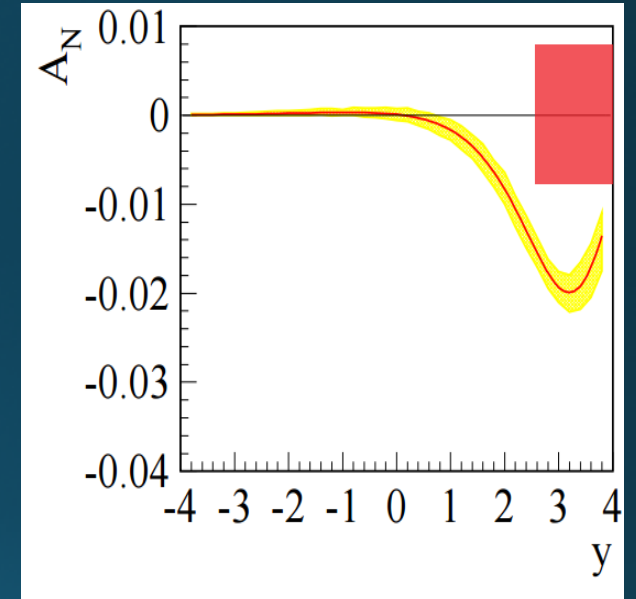


Transverse Momentum Distributions [page 18]

- RHIC will test TMD factorization and evolution via measurements of the single spin asymmetry A_{UT} of reconstructed W^+ , W^- and Z^0 bosons and forward Drell-Yan e^+e^- pairs.
- Asymmetries also provide new constraints on sea-quark Sivers functions.



BEFORE "Evolution"



AFTER "Evolution"

DATA : $p+p \sqrt{s} = 500$ GeV 400 pb^{-1}

DETECTOR: W/Z needs EMCal and charge sign discrimination for mid-rapidity tracks. DY needs EMCal + pre/post shower for QCD background suppression.